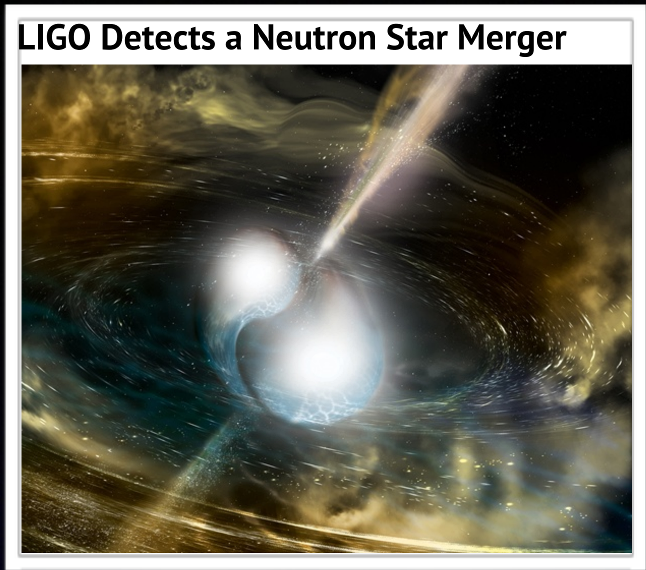
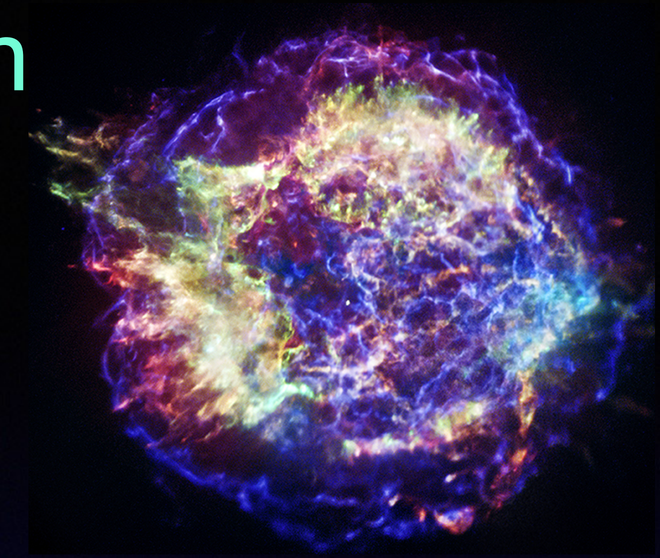
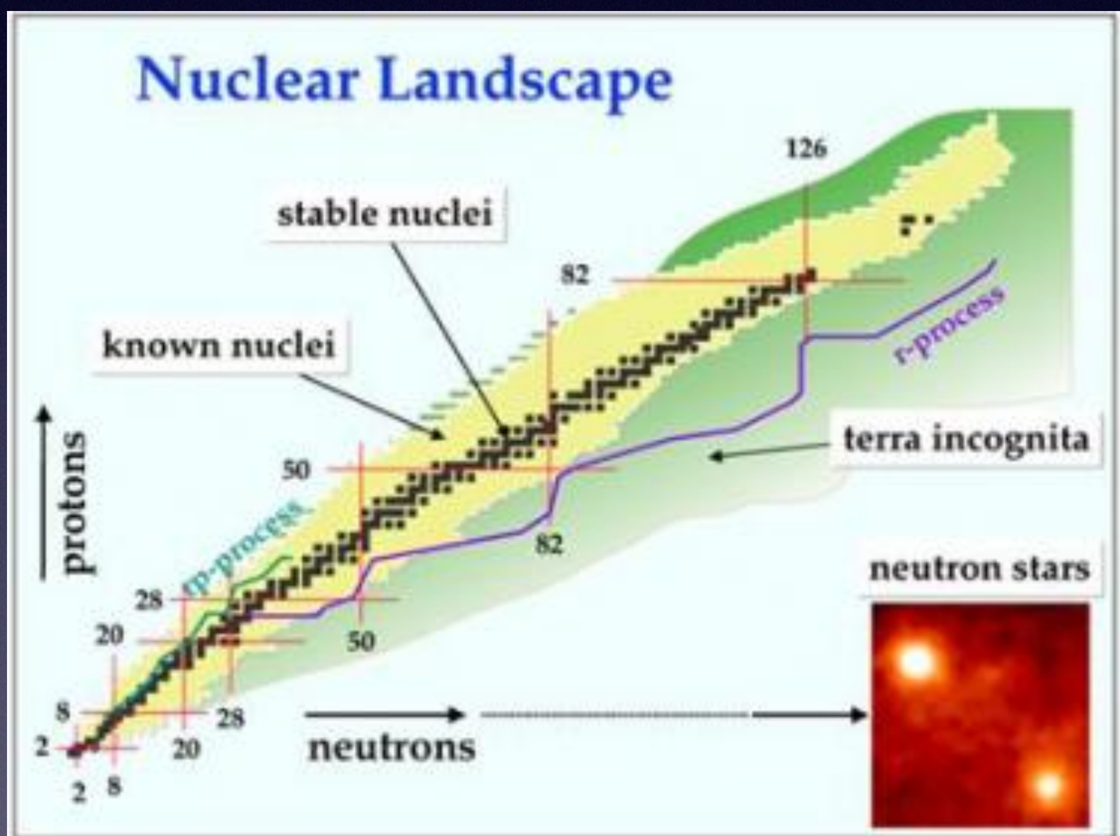


Neutron rich matter on heaven and earth in the new era of multi-messenger Astronomy

Sala Manuel Sandoval Vallarta

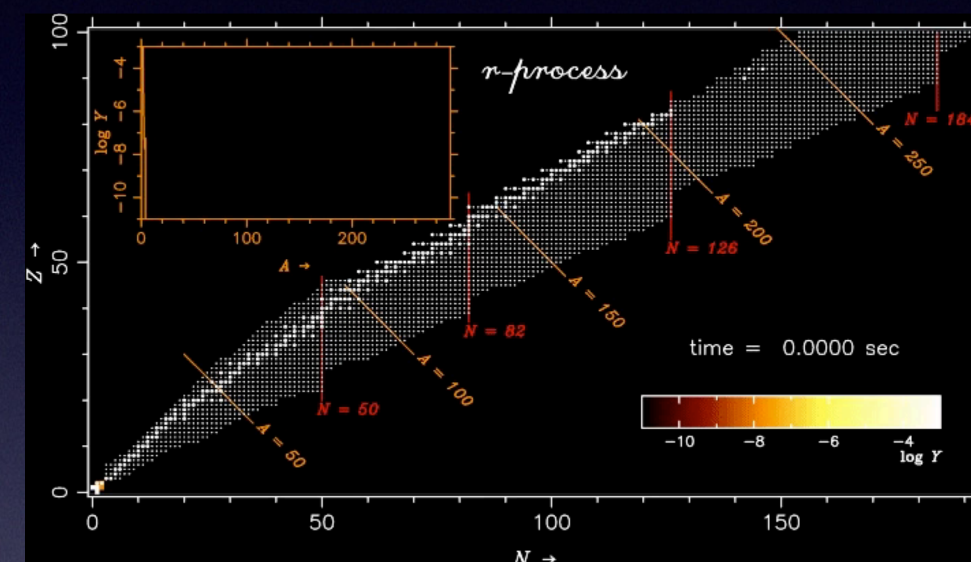
UNAM - March 20, 2019

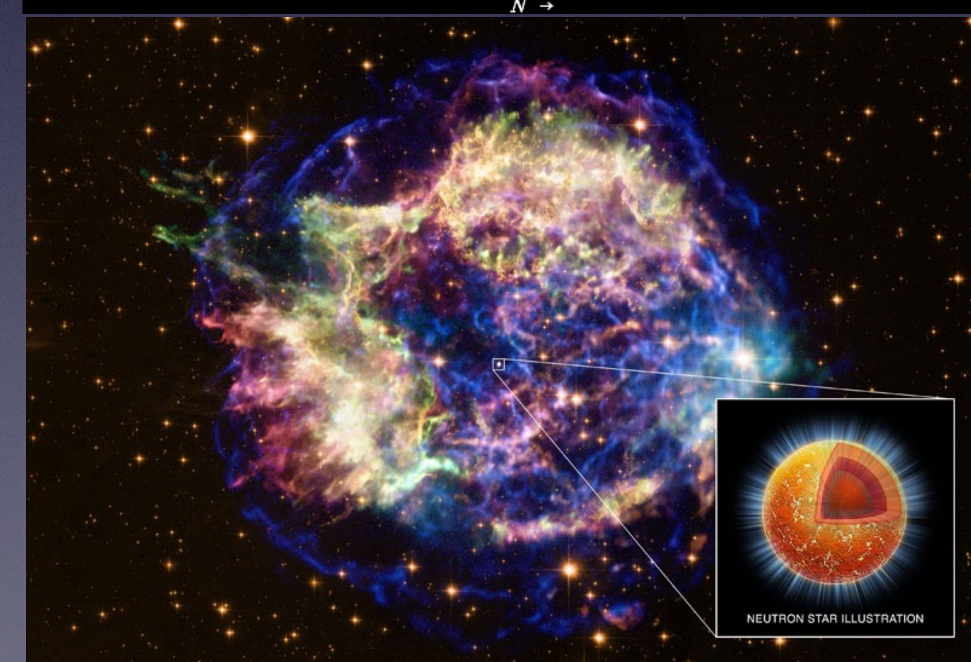




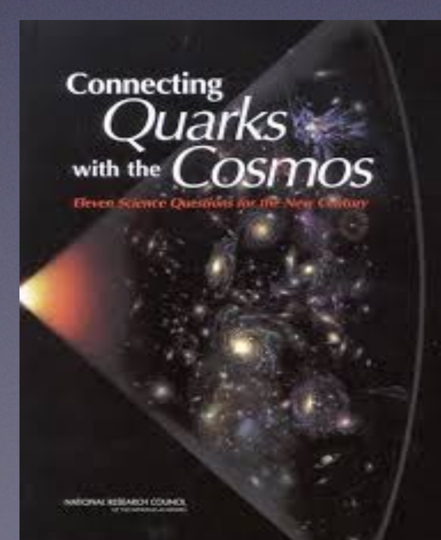
How were the heavy elements from iron to uranium made?

Are there new states of matter at ultrahigh temperatures and densities?





11 Science Questions for the New Century.



Manuel Sandoval Vallarta

- Guggenheim fellow in Germany under Einstein, Planck, Schrodinger, and Heisenberg (1927)
- While at MIT, Vallarta supervised Feynman's first ever scientific publication (1939) "The Scattering of Cosmic Rays by the Stars of a Galaxy" PR. 55, 506

Professor Marcos Moshinsky
(1921-2009)
My First Physics Mentor!

The Scattering of Cosmic Rays by the Stars of a Galaxy

The problem dealt with in this note may be formulated in the following way: imagine a galaxy of N stars, each carrying a magnetic dipole of moment μ_n ($n=1, 2, \cdots N$) and assume that the density, defined as the number of stars per unit volume, varies according to any given law, while the dipoles are oriented at random because of their very weak coupling. Under this condition the resultant field of the whole galaxy almost vanishes. Let there be an isotropic distribution of charged cosmic particles entering the galaxy from outside. Our problem is to find the intensity distribution in all directions around a point within the galaxy. Its importance arises from the fact that if the dis-

be emphasized that they apply only to the case in which there is no resultant magnetic field for the whole galaxy, such as would exist if the dipoles were oriented along preferential directions. In this case particles would either be imprisoned if born within the galaxy, or kept out, if coming from outside, depending on their energy and angular momentum. The reciprocal property of paths would then break down in general, but would still hold for any allowed direction at any point within the galaxy.

M. S. Vallarta
R. P. Feynman

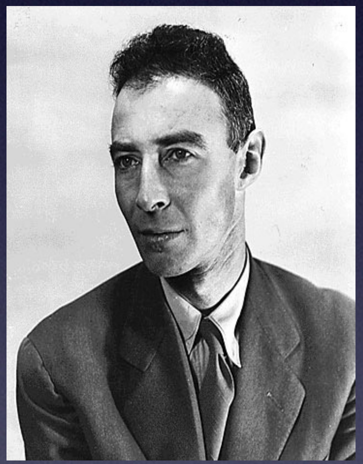
Massachusetts Institute of Technology,
Cambridge, Massachusetts,
February 15, 1939.

[1] A. H. Compton and I. A. Getting, Phys. Rev. **47**, 817 (1935). M. S. Vallarta, C. Graef and S. Kusaka, Phys. Rev. **55**, 1 (1939).
[2] See the discussion by E. J. Schremp, Phys. Rev. **54**, 153 (1938); and forthcoming papers by O. Godart and by A. Banõs, Jr.

Neutron Stars: Some Historical Facts

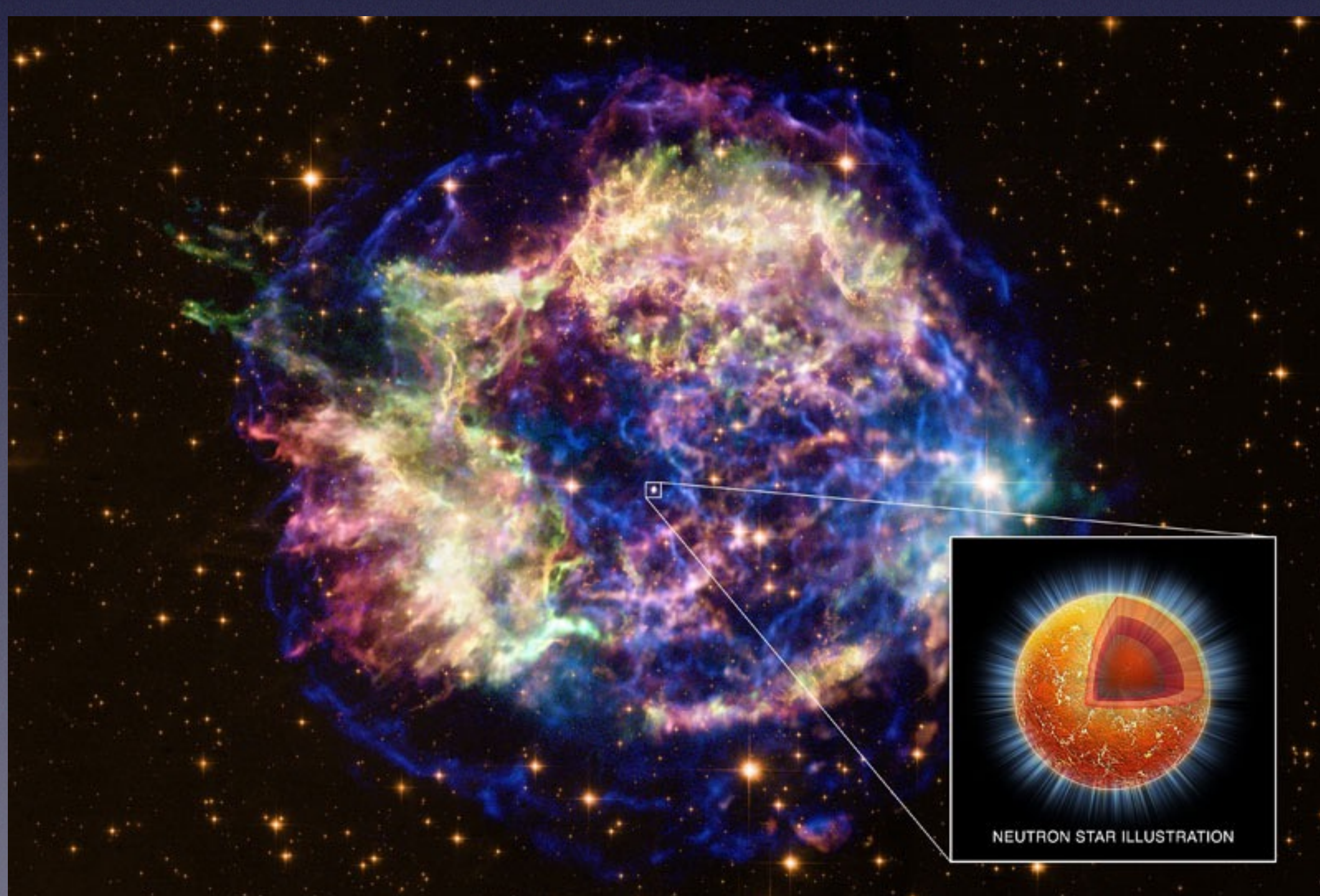
- Chandrasekhar shows that massive stars will collapse (1931)
- Chadwick discovers the neutron (1932)
(… predicted earlier by Majorana but never published)
- Baade-Zwicky introduce the concept of a neutron star (1933)
(… Landau mentions dense stars that look like giant nuclei)
- Oppenheimer-Volkoff use GR to compute the structure of neutron stars (1939)
(… predict $M_\star \simeq 0.7\, M_\odot$ as maximum neutron star mass)
- Jocelyn Bell discovers pulsars (1967)

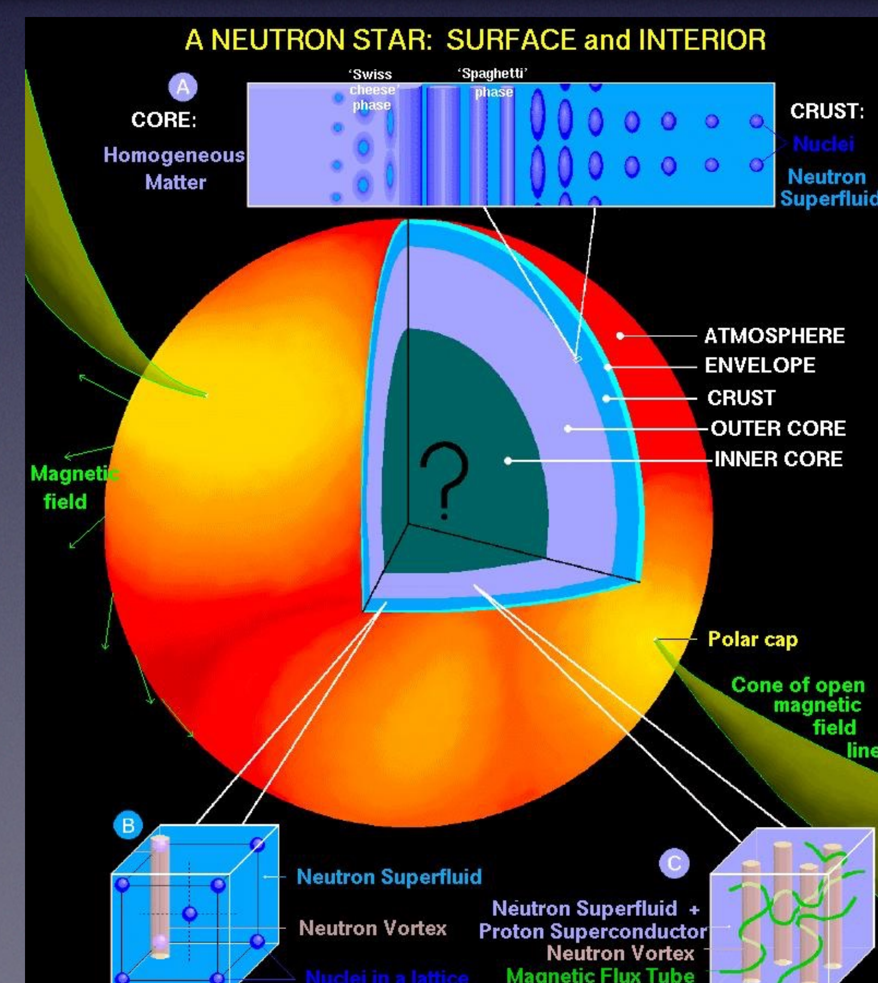
    Nobel awarded to Hewish and Ryle (1974)
    Awarded Special Breakthrough Prize (2018)
    donates prize money to help minority students



The Anatomy of a Neutron Star

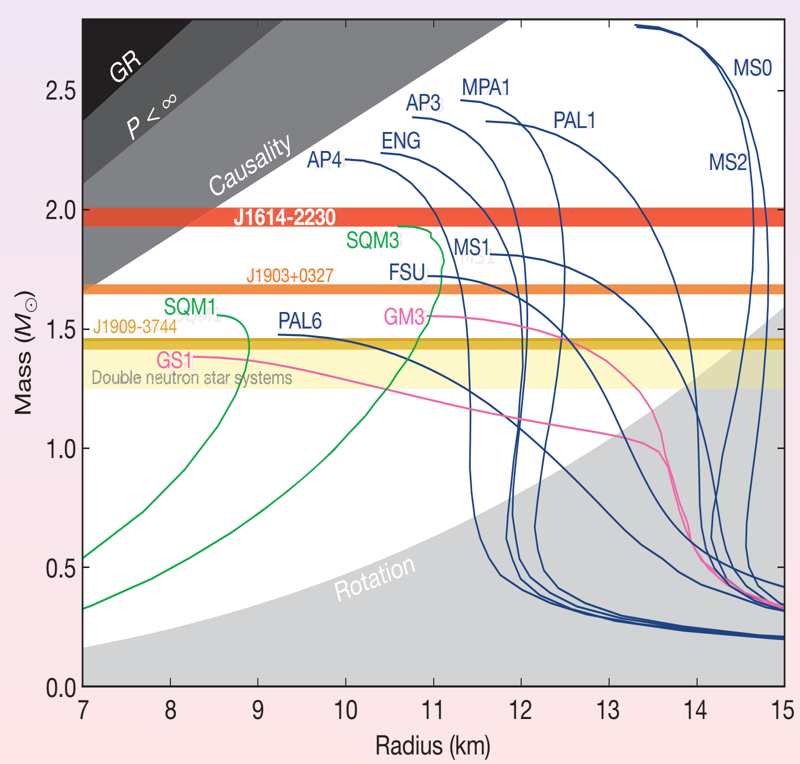
- Atmosphere (10 cm): Shapes Thermal Radiation ($L=4\pi\sigma R^2 T^4$)
- Envelope (100 m): Huge Temperature Gradient (10^8K $\leftrightarrow$ 10^6K)
- Outer Crust (400 m): Coulomb Crystal (Exotic neutron-rich nuclei)
- Inner Crust (1 km): Coulomb Frustration ("Nuclear Pasta")
- Outer Core (10 km): Uniform Neutron-Rich Matter (n,p,e,μ)
- Inner Core (?): Exotic Matter (Hyperons, condensates, quark matter)





Neutron Stars: The Nuclear Physics Connection

- Neutron stars are the remnants of massive stellar explosions (CCSN)
  - Bound by gravity — NOT by the strong force
  - Catalyst for the formation of exotic state of matter
  - Satisfy the Tolman-Oppenheimer-Volkoff equation ($v_{esc}/c \sim 1/2$)
- Only Physics that the TOV equation is sensitive to: *Equation of State*
  - EOS must span about 11 orders of magnitude in baryon density
- *Increase from 0.7→ 2 M_{sun} transfers ownership to Nuclear Physics!*
- Predictions on stellar radii differ by several kilometers!



$$\frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r)$$

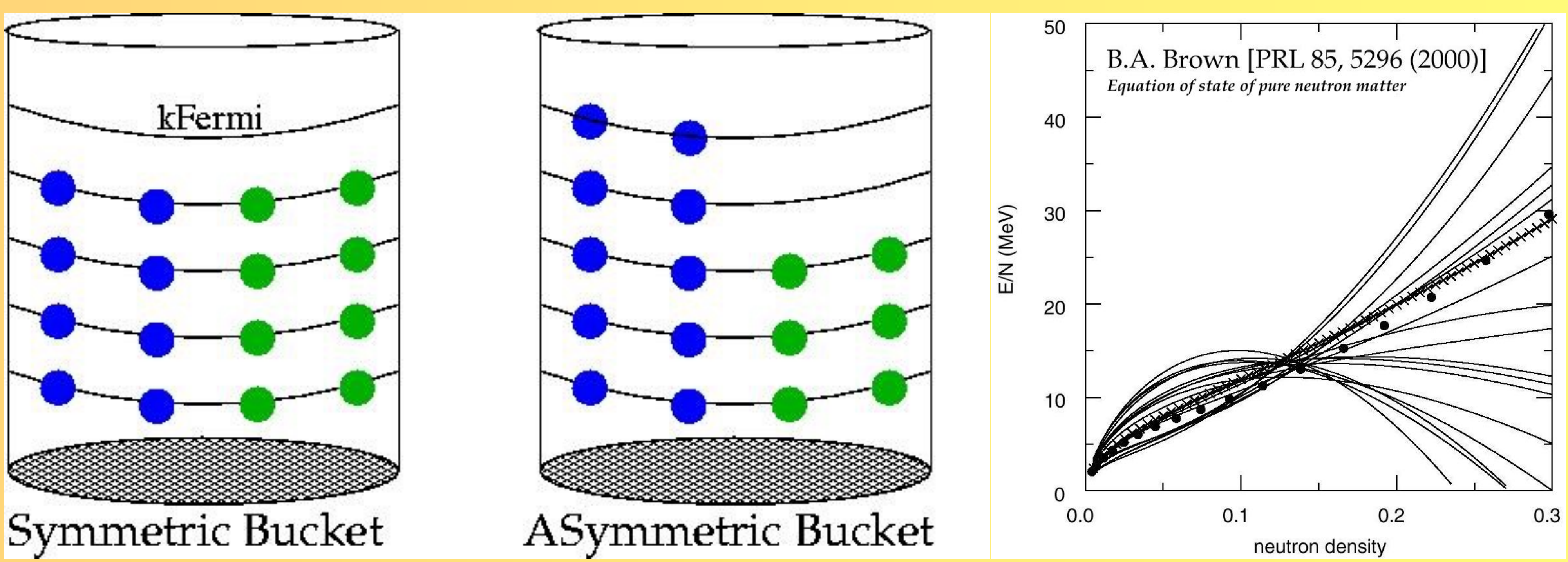
$$\frac{dP}{dr} = -G\frac{\mathcal{E}(r)M(r)}{r^2}\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

Need an EOS: $P = P(\mathcal{E})$ relation

$\boxed{\text{Nuclear Physics Critical}}$

The Equation of State of Neutron-Rich Matter

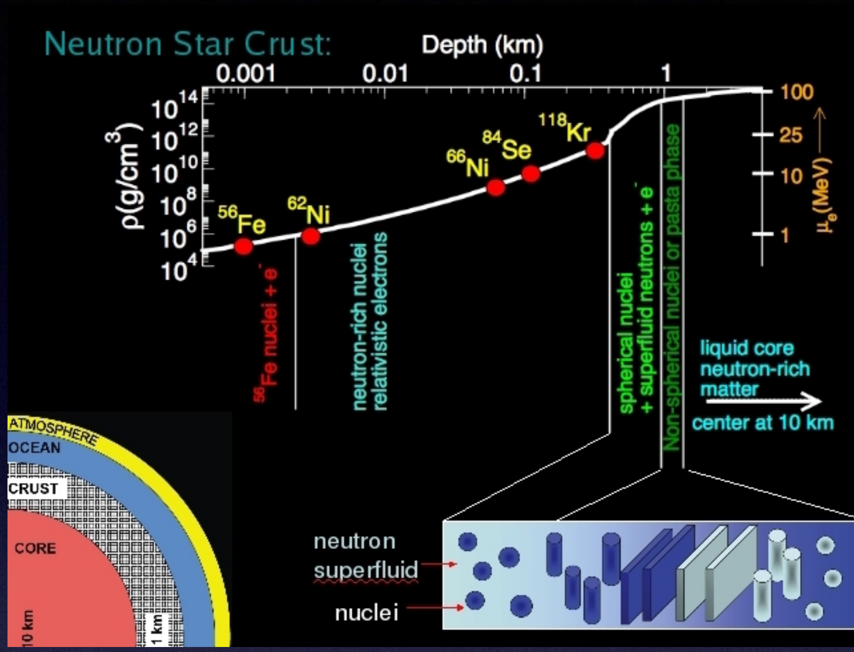
- The EOS of *T=0* asymmetric matter: α=(N-Z)/A; x=(ρ−ρ_0)/3ρ_0;
  ρ_0 $\simeq$0.15 fm^{-3} — saturation density ↔ nuclear density
  $$\mathcal{E}(\rho,\alpha) \simeq \mathcal{E}_0(\rho) + \alpha^2\mathcal{S}(\rho) \simeq \left(\epsilon_0 + \frac{1}{2}K_0x^2\right) + \left(J + Lx + \frac{1}{2}K_{\rm sym}x^2\right)\alpha^2$$
- Symmetric nuclear matter saturates "well" understood:
- Density dependence of symmetry poorly constrained:
  - J $\simeq$30 MeV — symmetry energy ↔ masses of neutron-rich nuclei
  - *L$\simeq$? — symmetry slope ↔ neutron skin of ^{208}Pb at JLab!*



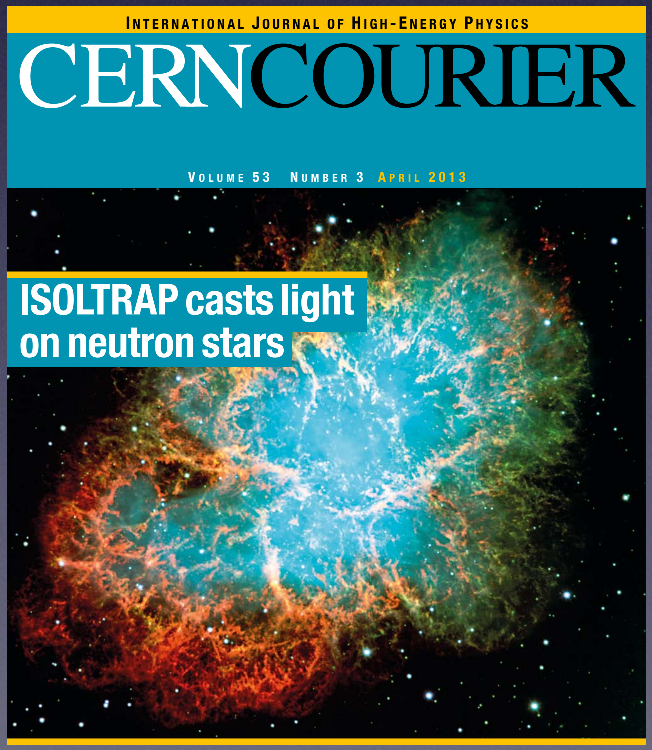
The Composition of the Outer Crust
Enormous sensitivity to nuclear masses

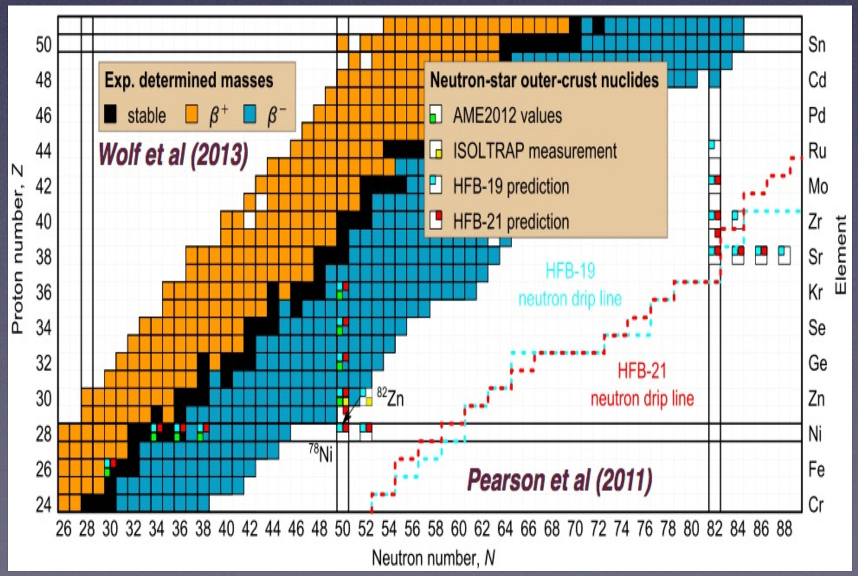
- System unstable to cluster formation
  - BCC lattice of neutron-rich nuclei imbedded in e-gas
- Composition emerges from relatively simple dynamics
  - Competition between electronic and symmetry energy

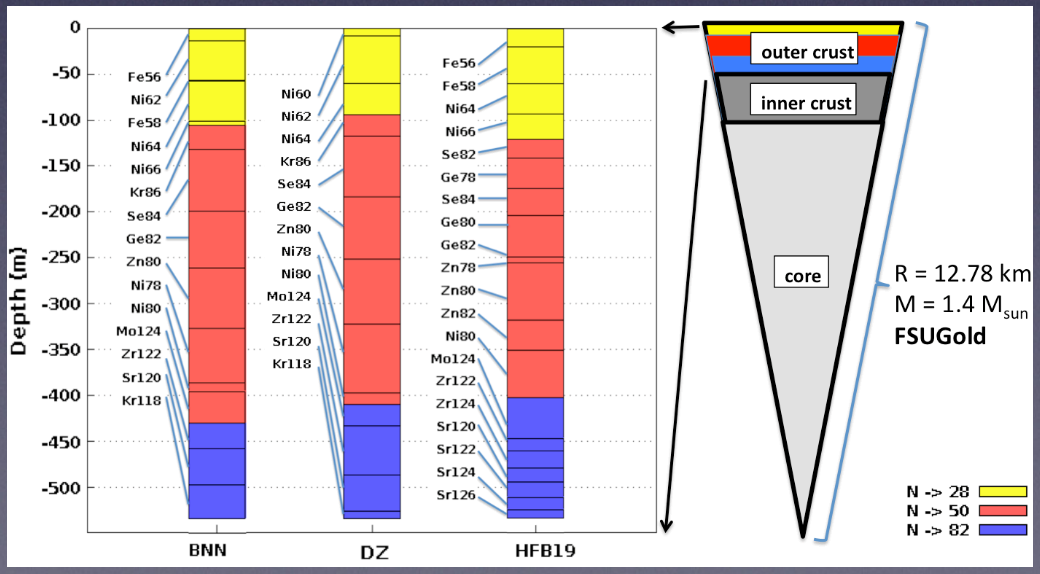
$$E/A_{\rm tot} = M(N,Z)/A + \frac{3}{4} Y_e^{4/3} k_{\rm F} + {\rm lattice}$$



- Precision mass measurements of exotic nuclei is essential
  - For neutron-star crusts and r-process nucleosynthesis



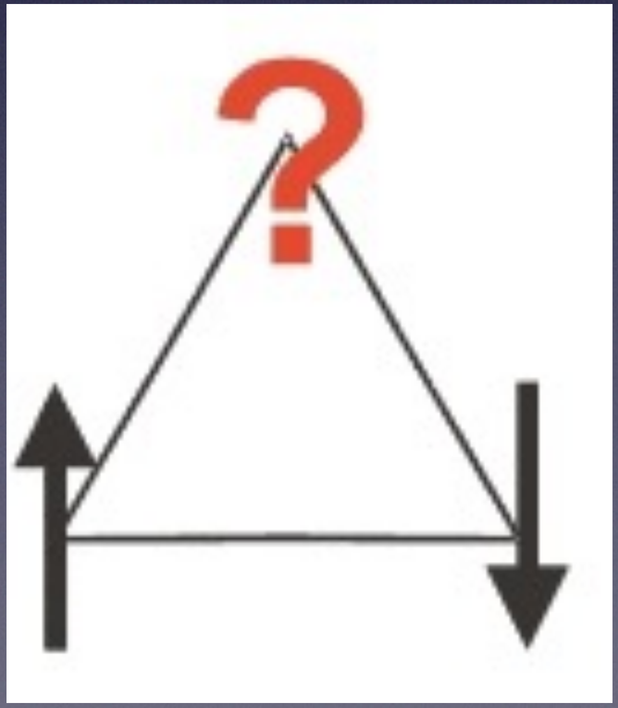


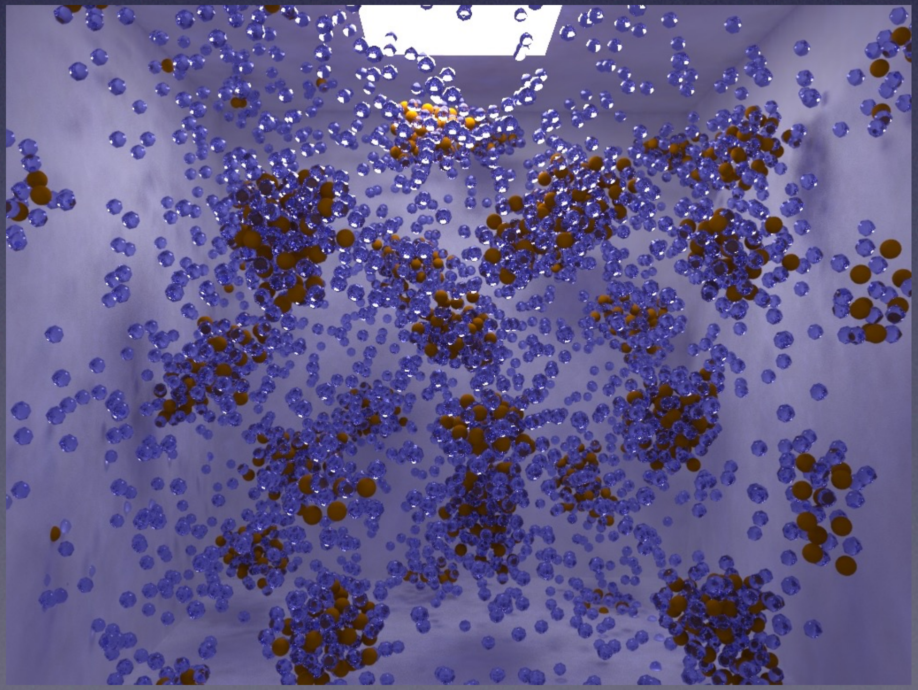


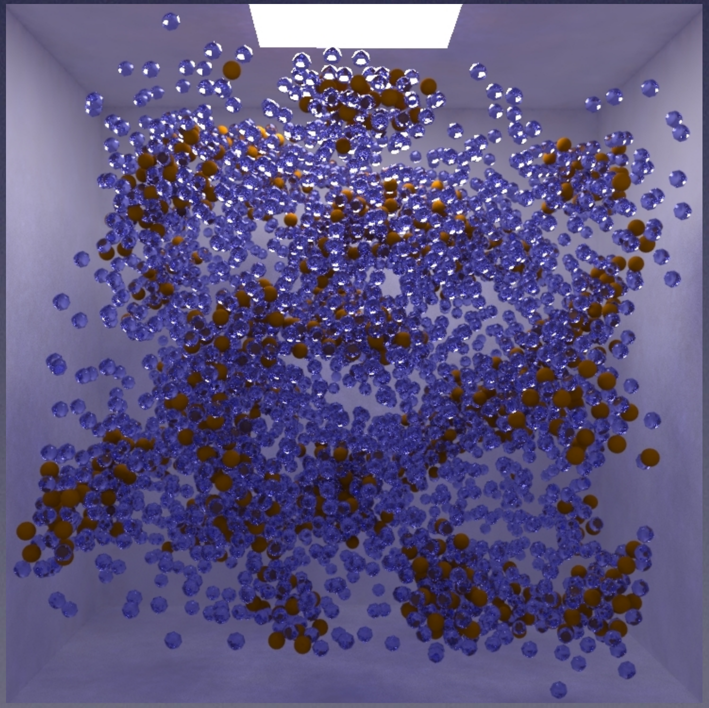
The Intriguing Inner Crust

- Top Layers: Coulomb Crystal of n-rich nuclei immersed in e- gas
  - … and a superfluid neutron vapor critical for glitches
- Bottom Layers: Coulomb frustration ⟶ *"Nuclear Pasta"*

- Emergent from a dynamical (or geometrical) competition
  - Impossible to simultaneously minimize all elementary interactions
  - Emergence of a multitude of topologically distinct (quasi) ground states
  - Universal in complex systems (low-D magnets, correlated e-, …)



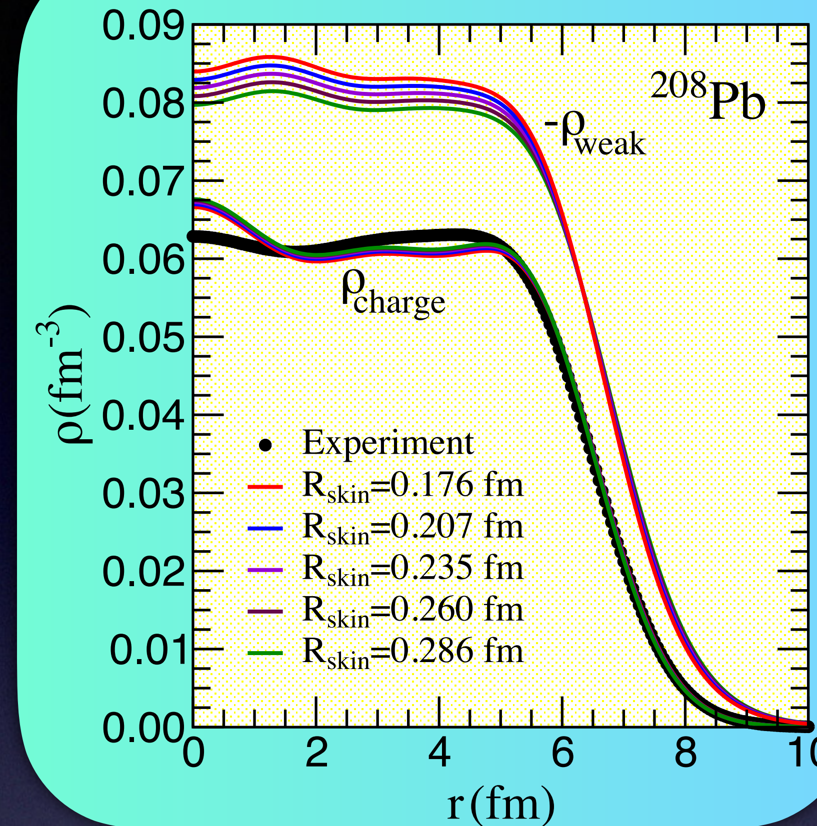


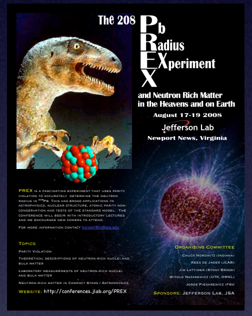


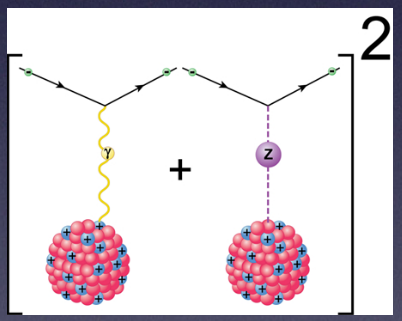
Tidal Polarizability extremely sensitive to the crustal dynamics!

The Quest for L at JLAB: R_{skin} as a proxy for L

- PREX@JLAB: First electroweak (clean!) evidence in favor of Rskin in Pb
- Precision hindered by radiation issues
  - Excellent control of systematic uncertainties
  - Statistical uncertainties 3 times larger than promised: Rskin=0.33(16)fm
- PREX-II and CREX to run in 2019
  - Original goal of 1% in neutron radius





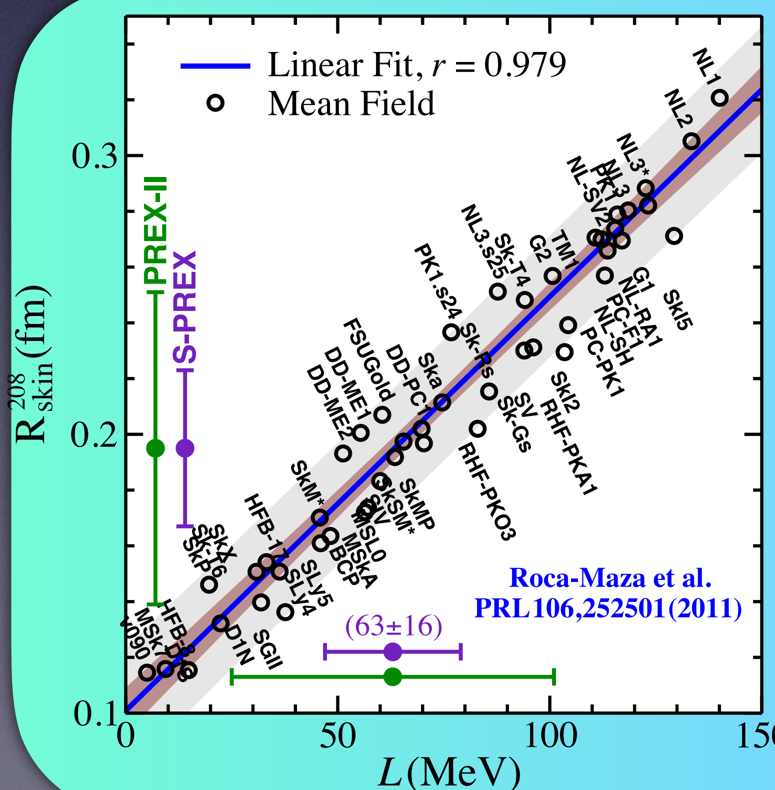


$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{Q_{\mathrm{wk}}F_{\mathrm{wk}}(Q^2)}{ZF_{\mathrm{ch}}(Q^2)}$$

- Neutral weak-vector boson Z_0 couples preferentially to neutrons
- PV provides a clean measurement of neutron densities (and R_n)

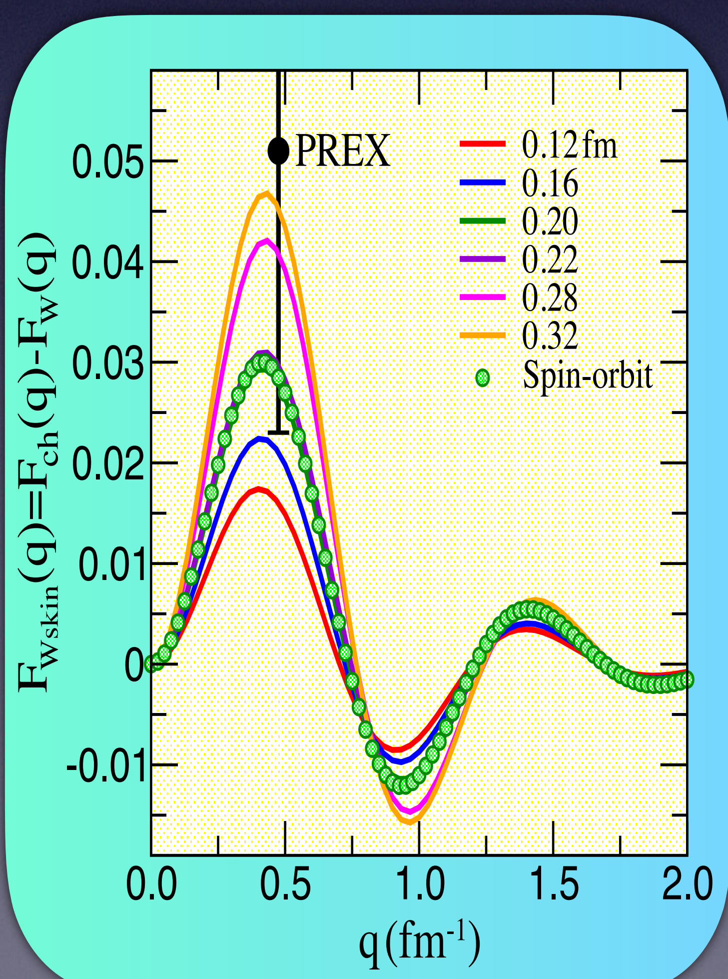
	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

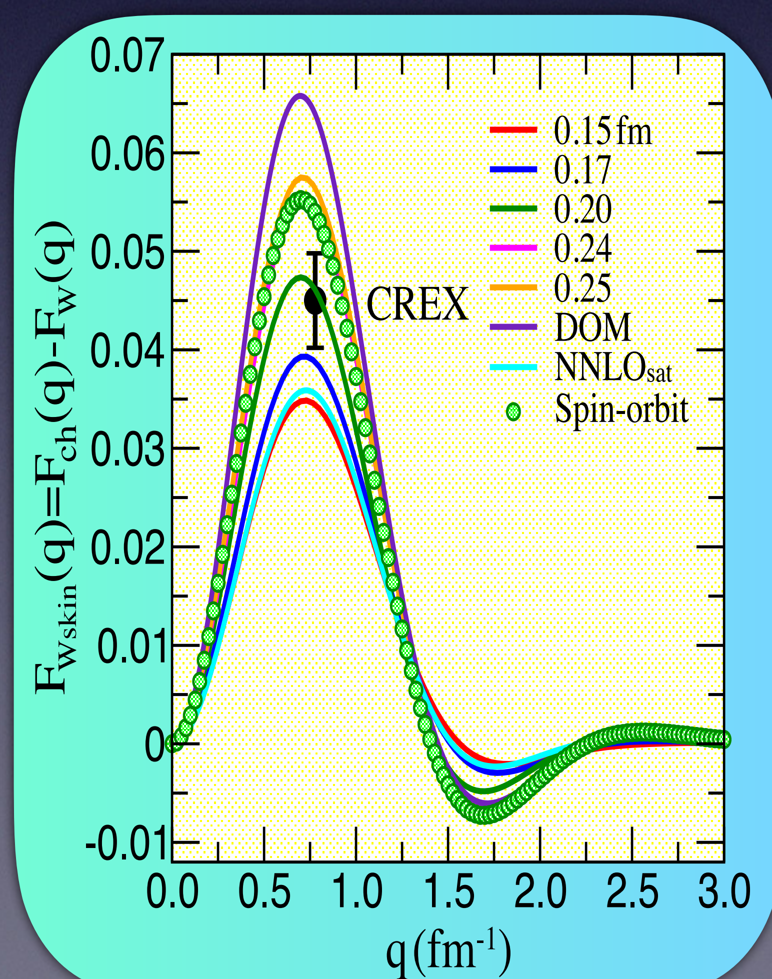
$$g_{\mathrm{v}} = 2t_z - 4Q\sin^2\theta_{\mathrm{W}} \approx 2t_z - Q$$



The Future: PREX-II, CREX, and MREX

- PREX obtained $R_n - R_p = 0.33^{+0.16}_{-0.18}\,\mathrm{fm}$
- PREX-II will improve error by a factor of 3 and determine L (pressure of PNM)
- MREX@Mainz will improve error by an additional factor of 2!
- CREX will provide bridge between ab-initio approaches (which can't predict the properties of ^{208}Pb) and nuclear DFTs (which can!)
- PREX-II and CREX to run in 2019 will provide fundamental anchors for future measurements of exotic nuclei at FRIB





The weak-skin form factor

A model-independent observable

$$F_{\mathrm{Wskin}} \equiv F_{\mathrm{ch}} - F_{\mathrm{wk}} \approx \frac{q^2}{6}\left(R_{\mathrm{wk}}^2 - R_{ch}^2\right) + \ldots$$

Spin-orbit currents

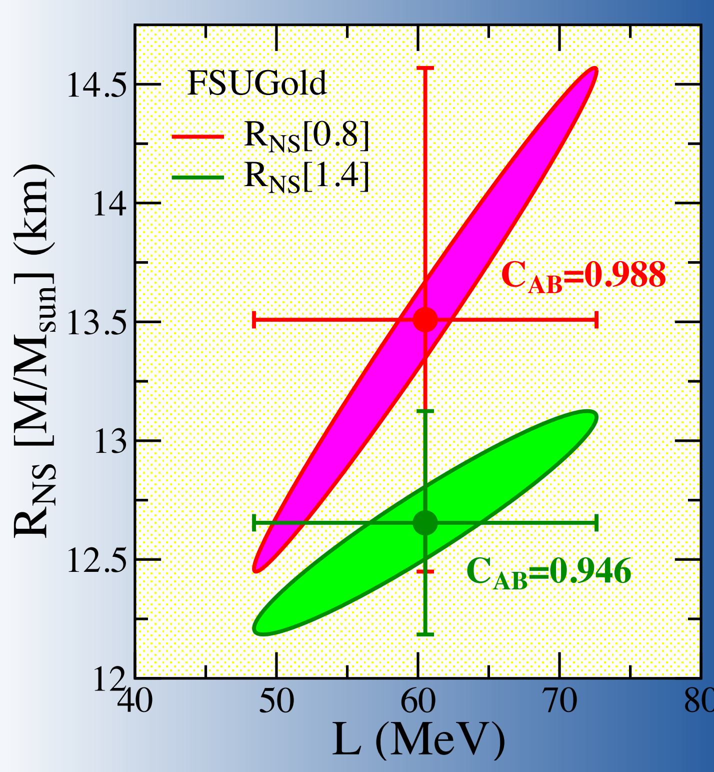
Vanish for fully occupied spin-orbit partners

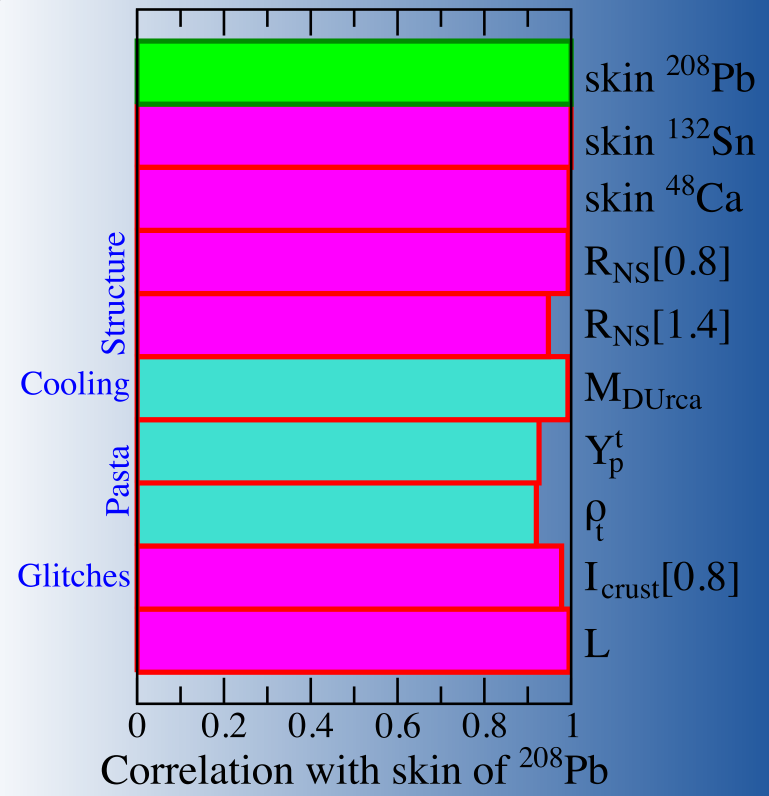
$$J^{\mu} = G_{\mathrm{E}}\gamma^{\mu} + \left(\frac{G_{\mathrm{M}} - G_{\mathrm{E}}}{1+\tau}\right)\boxed{\left[\tau\gamma^{\mu} + i\sigma_{\mu\nu}\frac{q_{\nu}}{2M}\right]}$$

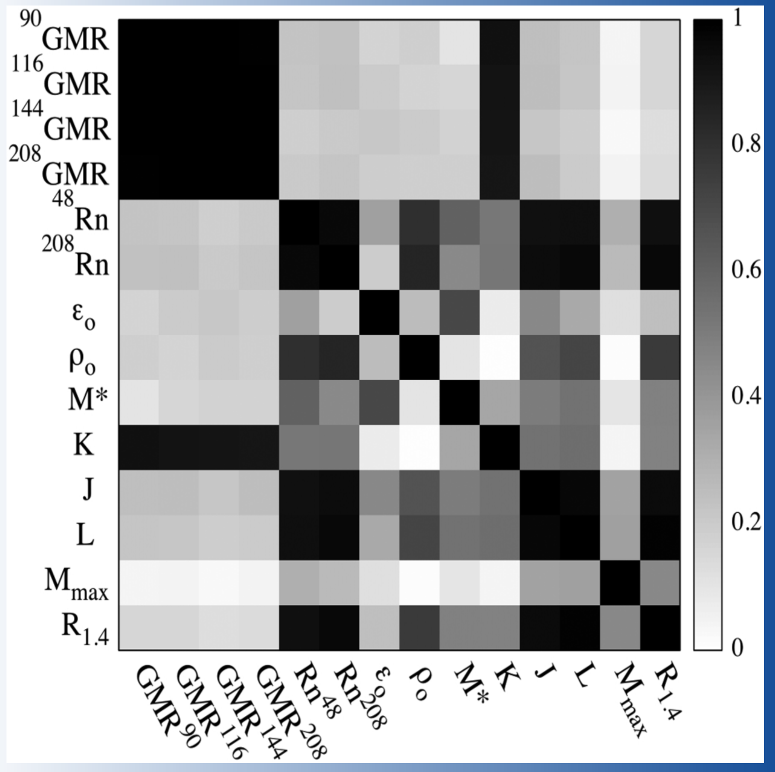
Heaven and Earth … and "L"

The enormous reach of the neutron skin

- Neutron-star radii are sensitive to the EOS near $2\rho_0$
  - Neutron star masses sensitive to EOS at much higher density
- Neutron skin correlated to a host of neutron-star properties
  - Stellar radii, proton fraction, enhanced cooling, moment of inertia
- Neutron skin of heavy nuclei and NS radii driven by same physics
  - Difference in length scales of 18 orders of magnitude!!

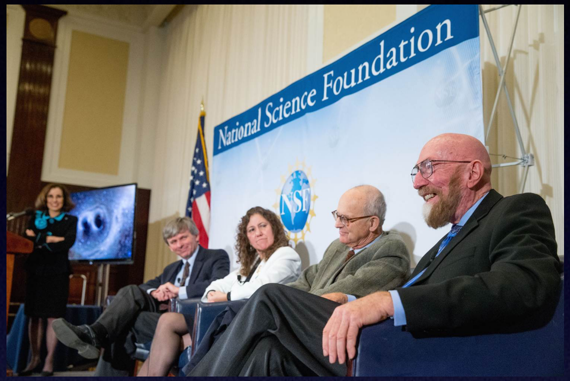


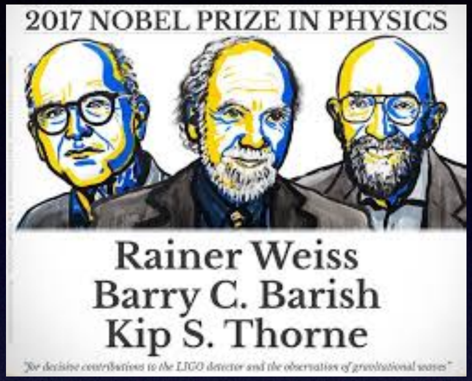




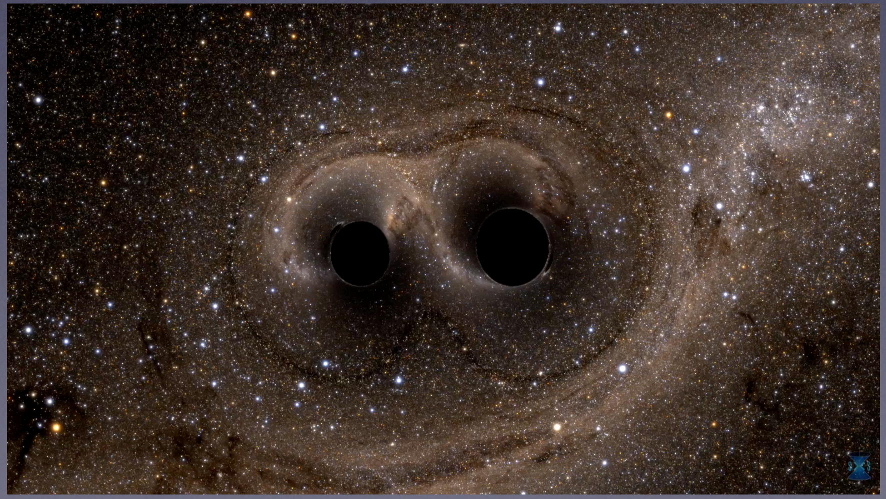
"We have detected gravitational waves; we did it!"

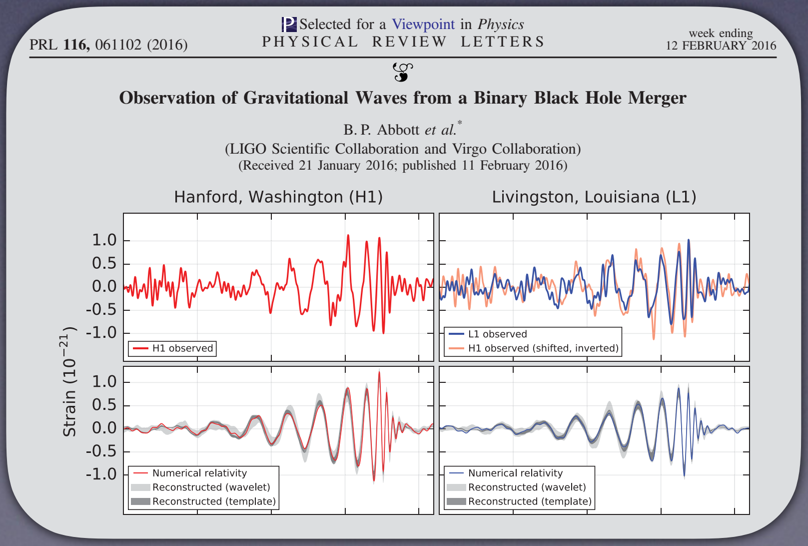
David Reitze, February 11, 2016





- **The dawn of a new era: GW Astronomy**
  - Initial black hole masses are 36 and 29 solar masses
  - Final black hole mass is 62 solar masses;
    3 solar masses radiated in Gravitational Waves!



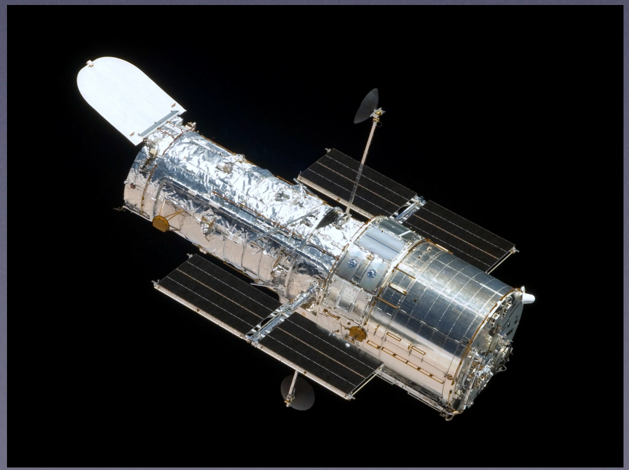


PRL **116,** 061102 (2016) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 12 FEBRUARY 2016

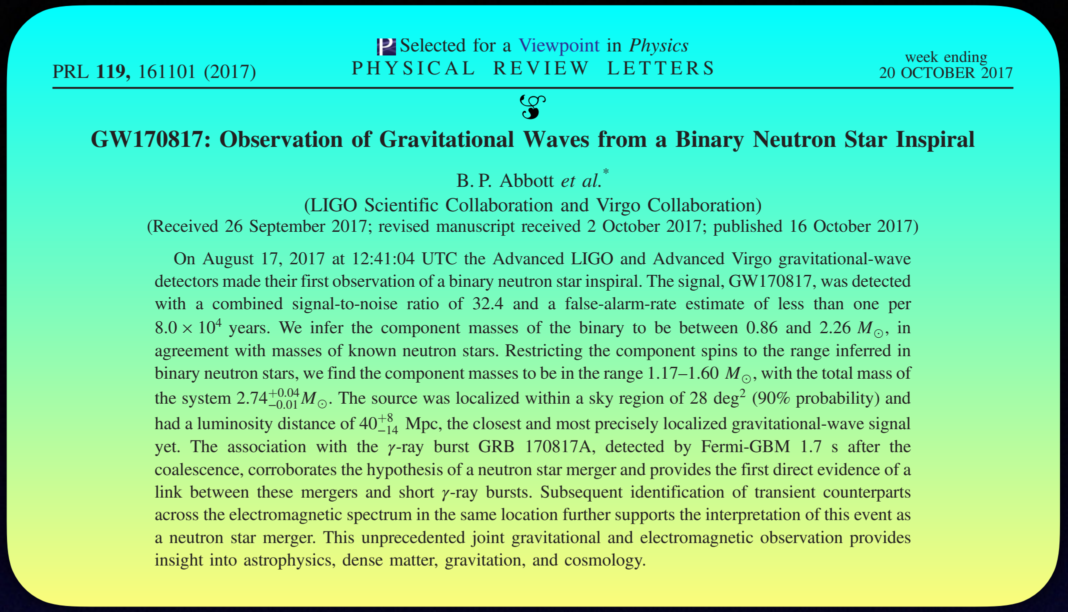
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

2017 BREAKTRHOUGH of the YEAR!



Historical first detection of gravitational waves from a binary neutron-star merger



PRL **119,** 161101 (2017) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

GW170817: A play in three acts

- **Act 1: Ligo-Virgo detect GW from BNS merger**
  - Source properties inferred from “matched filtering”
  - Extraction of “chirp” mass and “tidal polarizability”

    Stringent limits on the EOS of dense matter
- **Act 2: Fermi/Integral detect short γ-ray burst**
  - detected ~2 seconds after GW signal
  - Confirms long-held belief of the association between BNS merger and γ-ray bursts
- **Act 3: ~70 telescopes tracked the “kilonova”**
  - Afterglow of the explosive merger ~11 hours later
  - Powered by the radioactive decay of “r-process” elements

    BNS mergers as a critical site for the r-process!

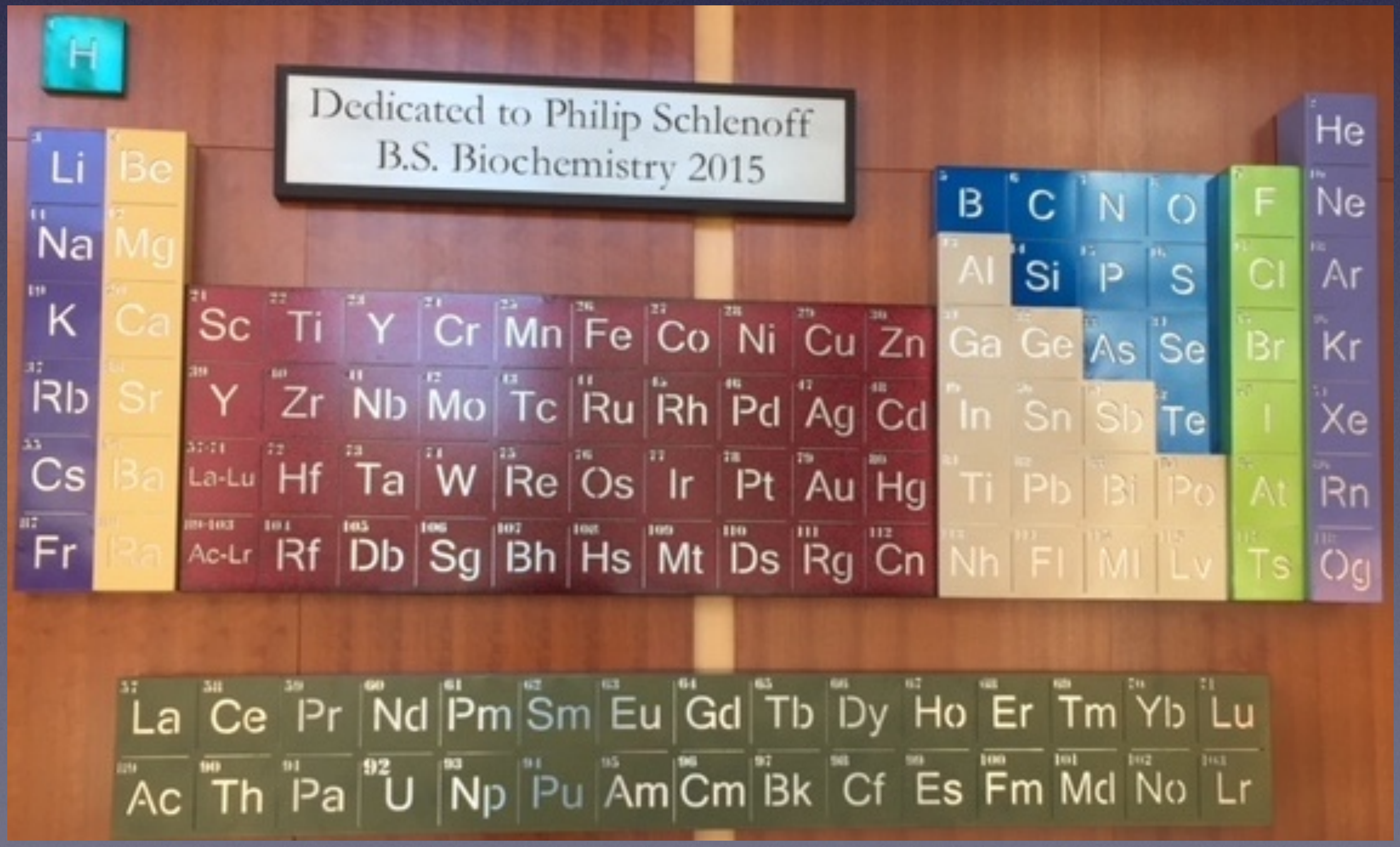
Neutron-star mergers create gravitational waves, light, and gold!

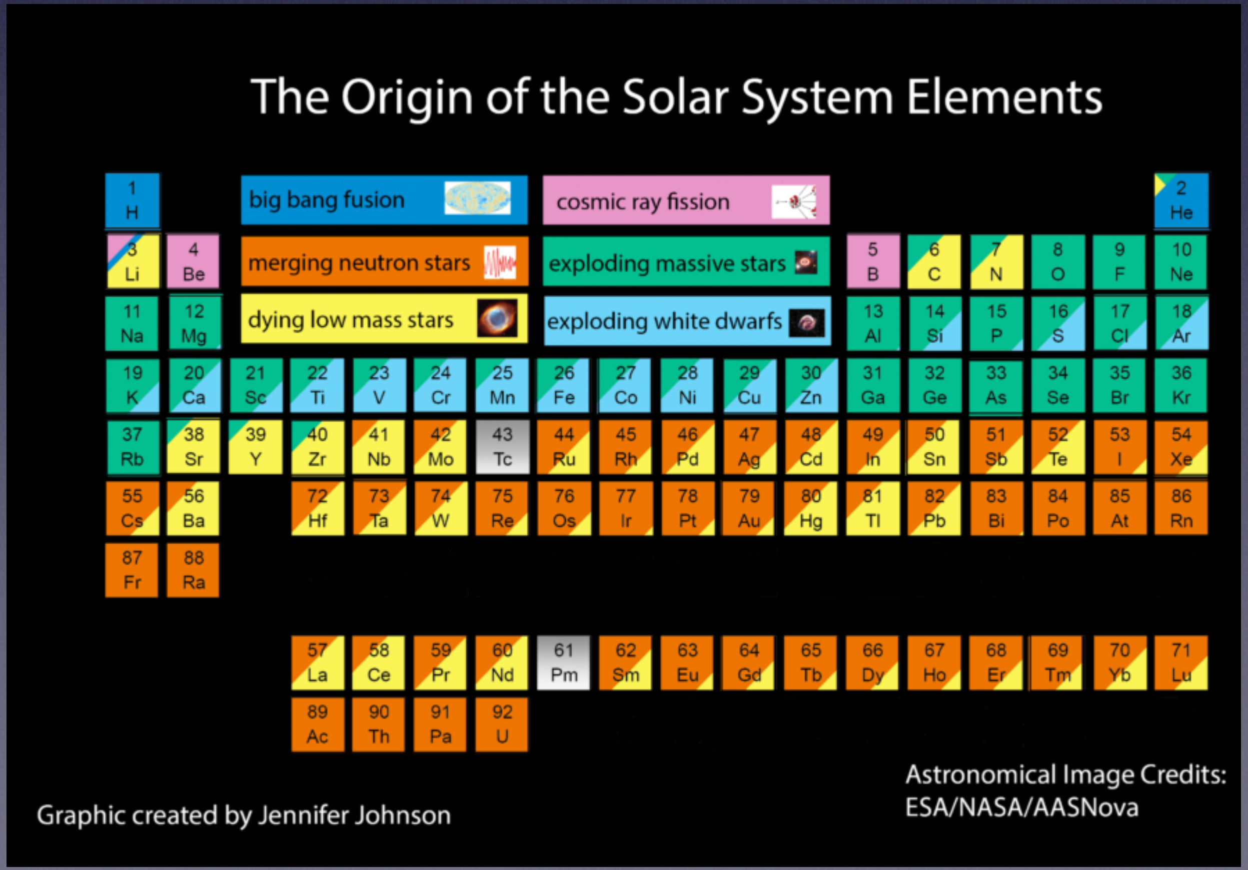
The New Periodic Table of the Elements

Abstract

MR Drout et al., Science - Dec, 2017

On 17 August 2017, gravitational waves (GWs) were detected from a binary neutron star merger, GW170817, along with a coincident short gamma-ray burst, GRB 170817A. An optical transient source, Swope Supernova Survey 17a (SSS17a), was subsequently identified as the counterpart of this event. We present ultraviolet, optical, and infrared light curves of SSS17a extending from 10.9 hours to 18 days postmerger. We constrain the radioactively powered transient resulting from the ejection of neutron-rich material. The fast rise of the light curves, subsequent decay, and rapid color evolution are consistent with multiple ejecta components of differing lanthanide abundance. The late-time light curve indicates that SSS17a produced at least ~0.05 solar masses of heavy elements, demonstrating that neutron star mergers play a role in rapid neutron capture (r-process) nucleosynthesis in the universe.





Nuclear Theory meets Machine Learning

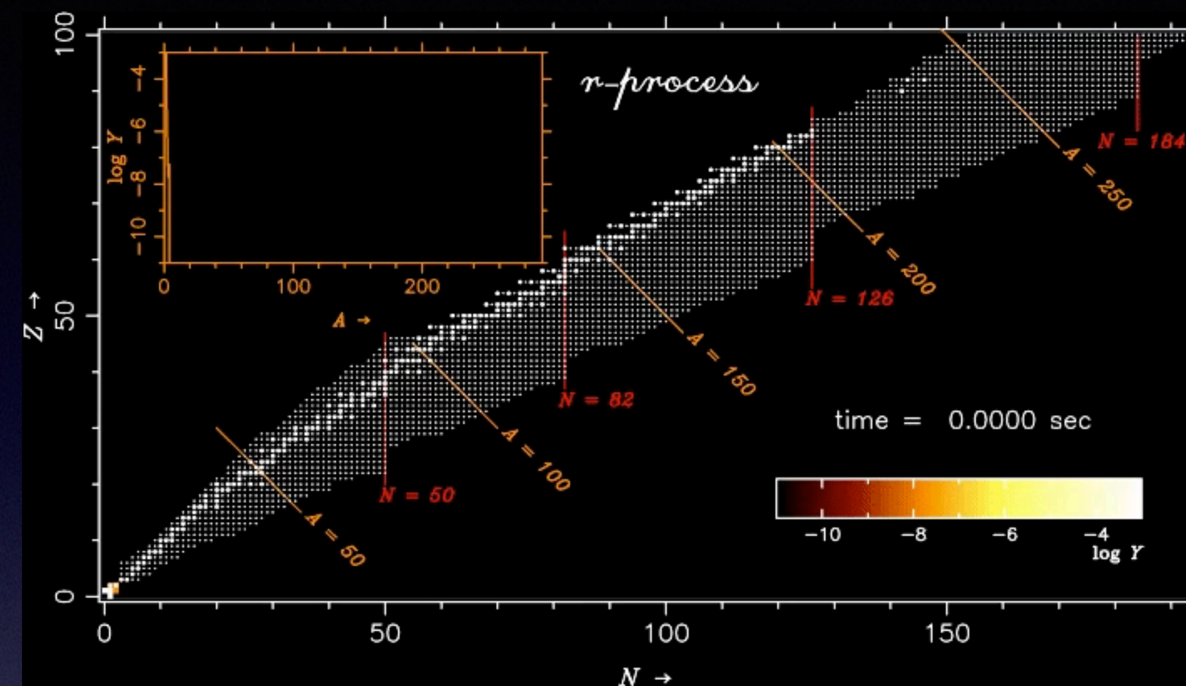
Masses of relevance to the r-process

PHYSICAL REVIEW C **92**, 035807 (2015)

Impact of individual nuclear masses on *r*-process abundances

M. R. Mumpower,[1,*] R. Surman,[1] D.-L. Fang,[2] M. Beard,[1] P. Möller,[3] T. Kawano,[3] and A. Aprahamian[1]
[1]*Department of Physics and Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2]*Department of Physics, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
(Received 28 May 2015; revised manuscript received 29 July 2015; published 15 September 2015)

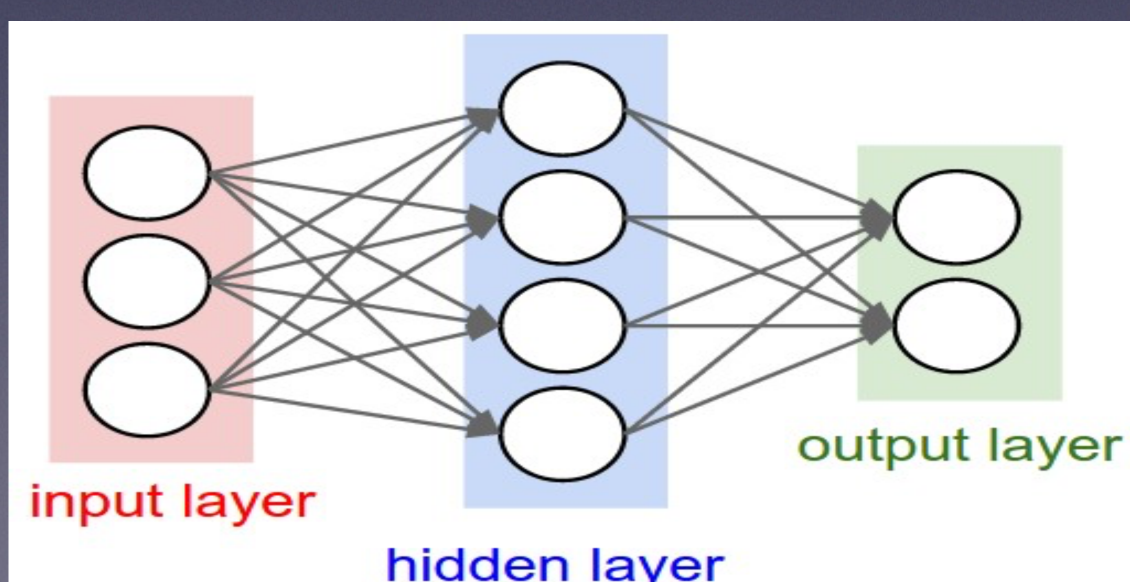
We have performed for the first time a comprehensive study of the sensitivity of *r*-process nucleosynthesis to individual nuclear masses across the chart of nuclides. Using the latest version (2012) of the Finite-Range Droplet Model, we consider mass variations of ±0.5 MeV and propagate each mass change to all affected quantities, including *Q* values, reaction rates, and branching ratios. We find such mass variations can result in up to an order of magnitude local change in the final abundance pattern produced in an *r*-process simulation. We identify key nuclei whose masses have a substantial impact on abundance predictions for hot, cold, and neutron star merger *r*-process scenarios and could be measured at future radioactive beam facilities.

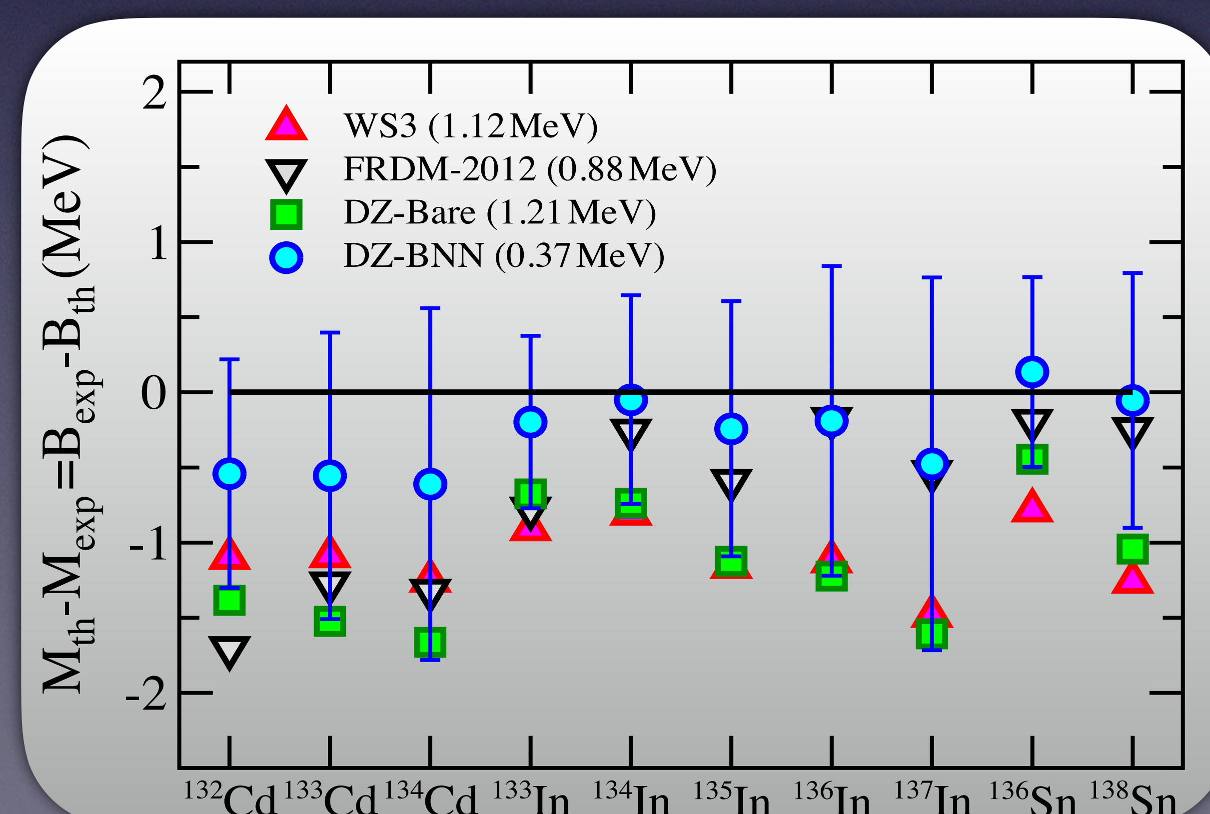


The paradigm:

Use DFT to predict nuclear masses
Train BNN by focusing on residuals

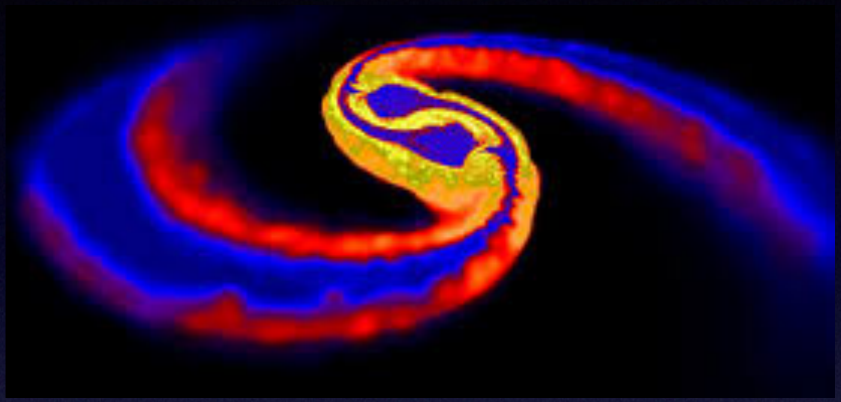
$$M(N,Z) = M_{DFT}(N,Z) + \delta M_{BNN}(N,Z)$$





Tidal Polarizability, Neutron-Star Radii, and the Equation of State

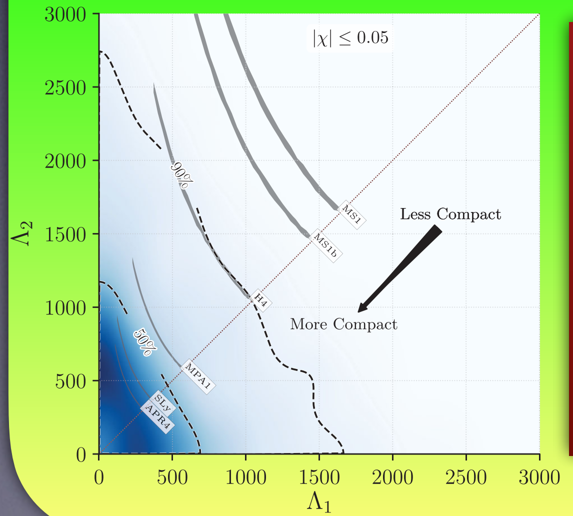
- **Electric Polarizability:**
  - Electric field induced a polarization of charge
  - A time dependent electric dipole emits electromagnetic waves: $P_i = \chi E_i$



- **Tidal Polarizability:**
  - Tidal field induces a polarization of mass
  - A time dependent mass quadrupole emits gravitational waves: $Q_{ij} = \Lambda \mathcal{E}_{ij}$

$$\Lambda \approx k_2 \left(\frac{c^2 R}{2GM}\right)^5 = k_2 \left(\frac{R}{R_s}\right)^5$$

the posterior shown in Fig. 4. We find that our constraints on Λ_1 and Λ_2 disfavor equations of state that predict less compact stars, since the mass range we recover generates Λ values outside the 90% probability region. This is con-



Equations of state with a very stiff symmetry energy (and very larger neutron star radii) are ruled out!

The tidal polarizability measures the "fluffiness" (or stiffness) of a neutron star against deformation

Neutron skins and neutron stars in the multi-messenger era

PHYSICAL REVIEW LETTERS **120,** 172702 (2018)

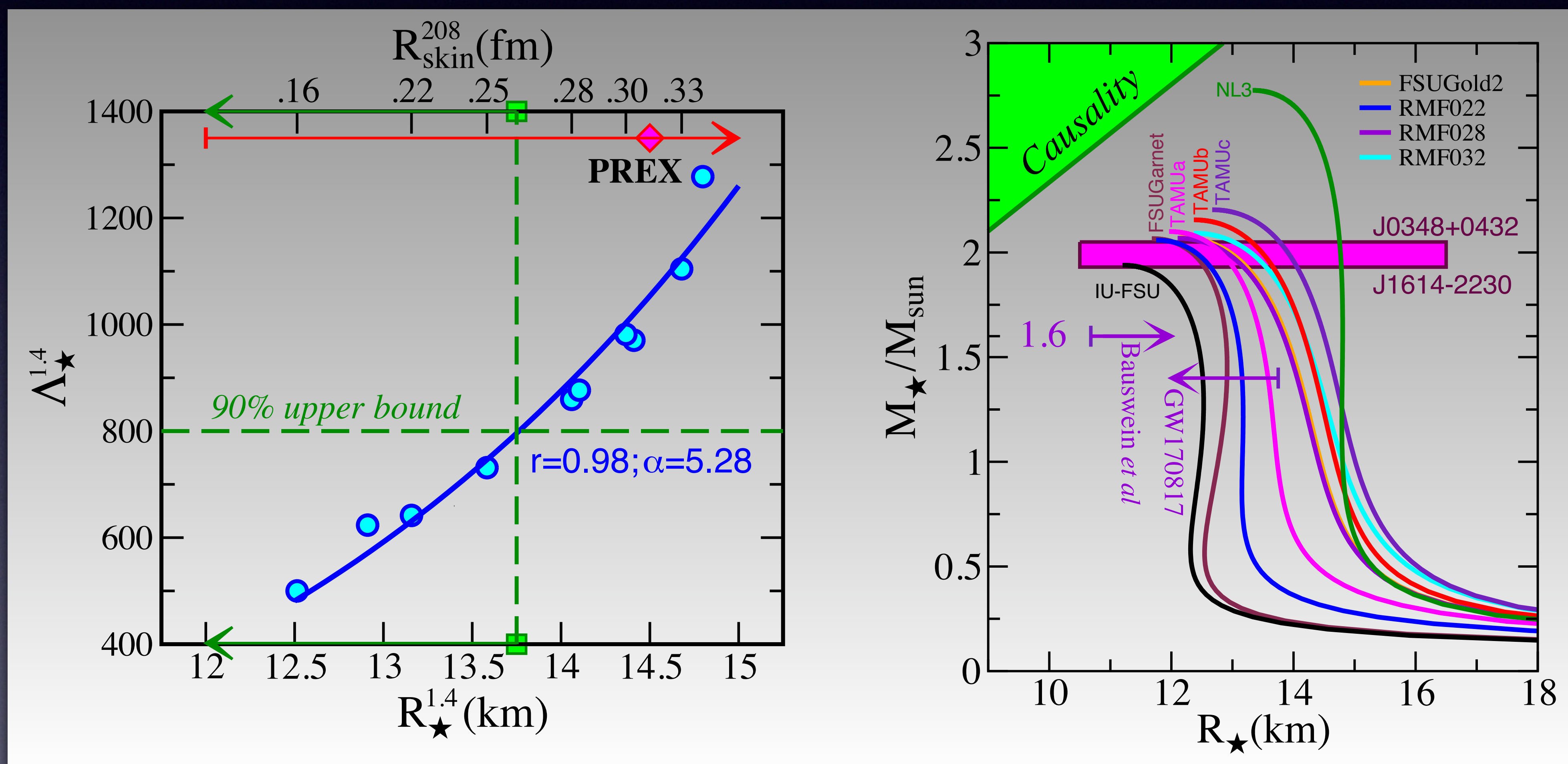
Editors' Suggestion | Featured in Physics

Neutron Skins and Neutron Stars in the Multimessenger Era

F. J. Fattoyev,[1,*] J. Piekarewicz,[2,†] and C. J. Horowitz[1,‡]

[1]*Center for Exploration of Energy and Matter and Department of Physics, Indiana University, Bloomington, Indiana 47405, USA*

[2]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*



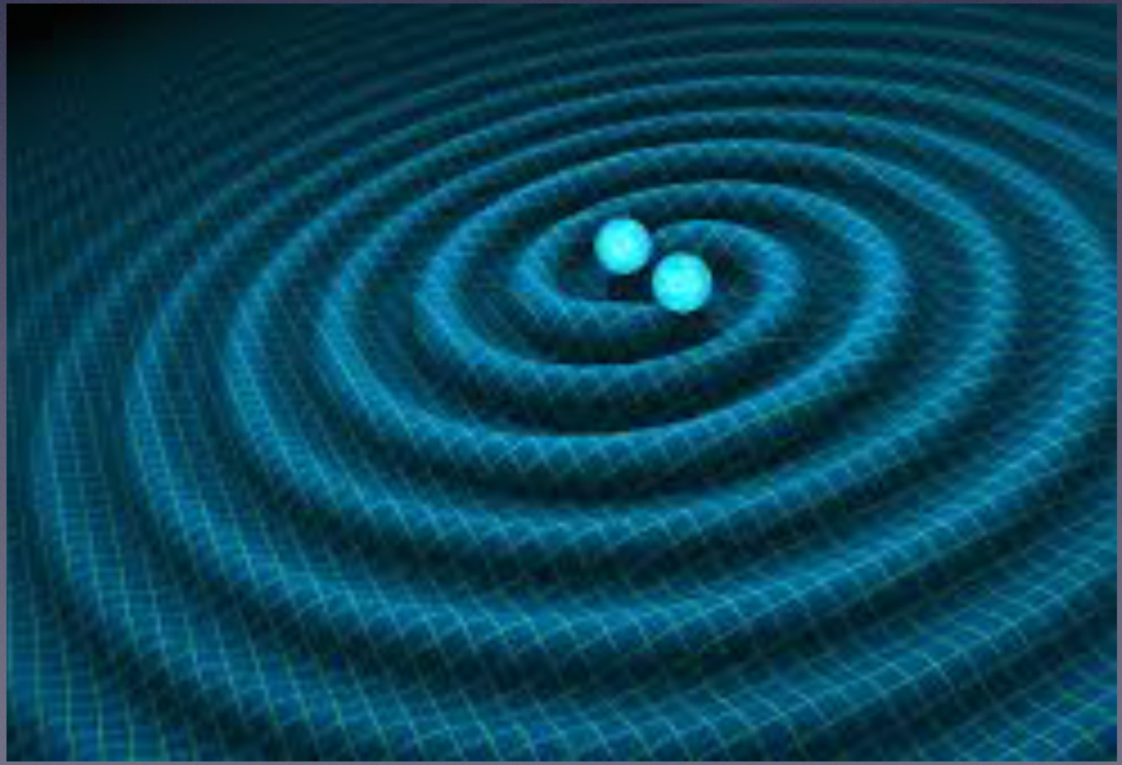
Exciting possibility: If PREX confirms that Rskin is large and LIGO-Virgo that NS-radius is small, this may be evidence of a softening of the EOS at high densities (phase transition?)

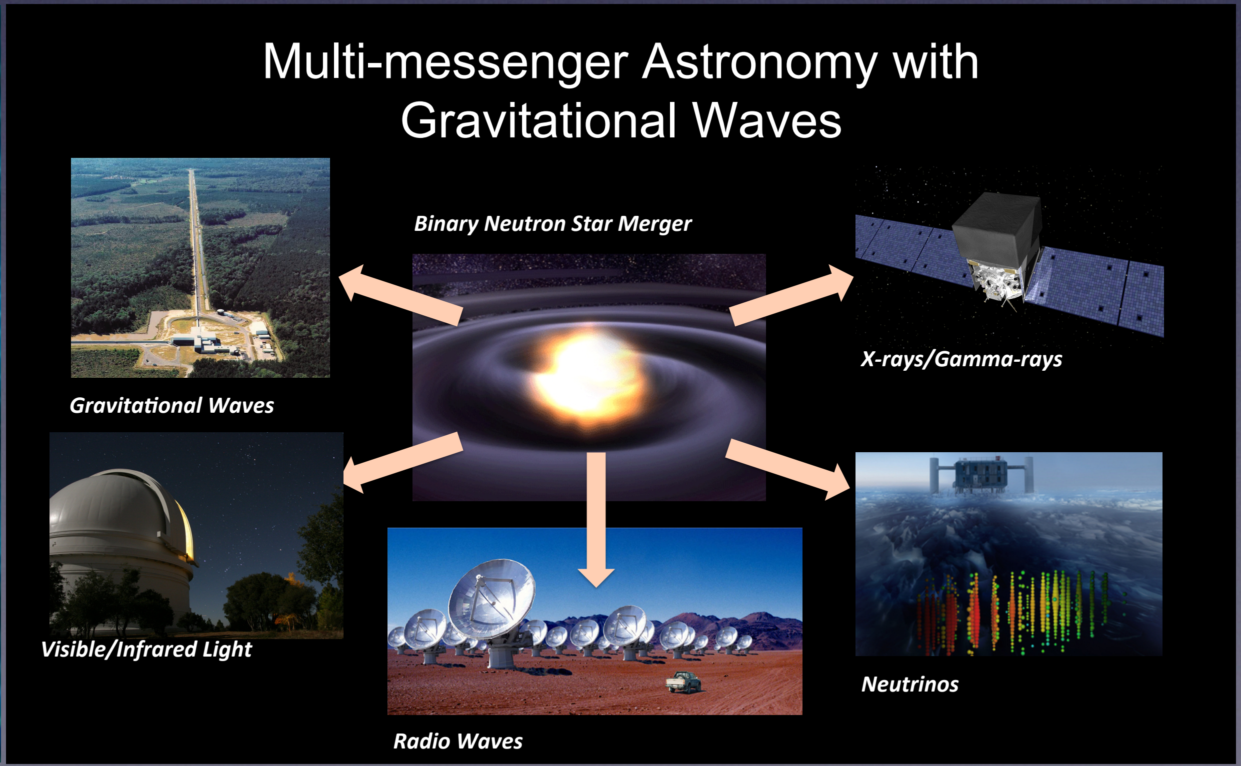
The very first observation of a BNS merger already provides a treasure trove of insights into the nature of dense matter!

Conclusions: It is all Connected

- Astrophysics: What is the minimum mass of a black hole?
- C.Matter Physics: Existence of Coulomb-Frustrated Nuclear Pasta?
- General Relativity: Can BNS mergers constrain stellar radii?
- Nuclear Physics: What is the EOS of neutron-rich matter?
- Particle Physics: What exotic phases inhabit the dense core?
- Machine Learning: Extrapolation to where no man has gone before?

Neutron Stars are the natural meeting place for interdisciplinary, fundamental, and fascinating physics!





My Collaborators

My FSU Collaborators

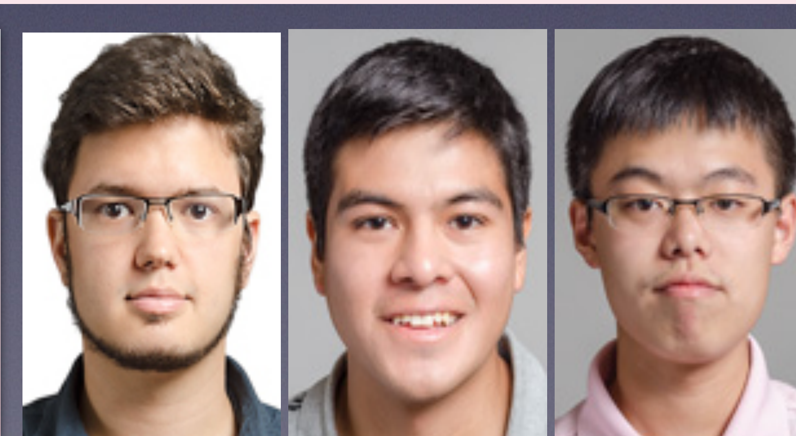
- Genaro Toledo-Sanchez
- Karim Hasnaoui
- Bonnie Todd-Rutel
- Brad Futch
- Jutri Taruna
- **Farrukh Fattoyev**
- **Wei-Chia Chen**
- **Raditya Utama**

My Outside Collaborators

- B. Agrawal (Saha Inst.)
- M. Centelles (U. Barcelona)
- G. Colò (U. Milano)
- C.J. Horowitz (Indiana U.)
- W. Nazarewicz (MSU)
- N. Paar (U. Zagreb)
- M.A. Pérez-Garcia (U. Salamanca)
- P.G.- Reinhard (U. Erlangen-Nürnberg)
- X. Roca-Maza (U. Milano)
- D. Vretenar (U. Zagreb)

The New Generation

- **Pablo Giuliani**
- **Daniel Silva**
- **Junjie Yang**



U.S. DEPARTMENT OF ENERGY | Office of Science

FLORIDA STATE UNIVERSITY VIRES ARTES MORES 1851